THE SPECTRUM OF *O CETI.**

BY JOEL STEBBINS.

On account of the great instrumental power required for the observation of the spectra of faint objects, changes in the spectra of long-period variable stars have not been well studied. In fact, there is no star which undergoes a large variation in brightness whose spectrum has been systematically followed from maximum to minimum, or *vice versa.* It is proposed to give here the results of a study of the spectrum of *o Ceti,* or *Mira,* made, at the suggestion of Director CAMPBELL, with the thirty-six-inch refractor of the Lick Observatory, from June, 1902, to January, 1903. During this period the star faded in brightness from 3.8 to 9.0 magnitude. The first photograph of the spectrum was obtained about three weeks after the predicted time of maximum, and a series of plates was secured, covering the interval to minimum. No negatives were obtained after the star had again begun to increase in brightness.

The most important articles concerning the spectrum of *Mira* are those of VOGEL,† SIDGREAVES,‡ and CAMPBELL.¶ Neither VOGEL nor SIDGREAVES followed the star long enough to find much change in its spectrum, and CAMPBELL'S work was mainly in connection with observations of the star for radial velocity, with the Mills spectrograph.

The spectrograph used in my observations was the one employed by Messrs. CAMPBELL and WRIGHT in their work on *Nova Persei* [L. O. Bulletin No. 8], designated as "Spectrograph I." It is the regular Mills spectrograph converted into a one-prism instrument. It gives good definition, on the same photograph, of the region from λ 3700 to λ 5600. Although this dispersion is only about one fifth of that of the three-prism instrument, it is enough to yield a very fair determination of velocity.

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† H. C. VOGEL. Ueber das Spectrum von *Mira Ceti.* Sitzungsberichte der Berlin Acad., 1896, p. 143.

‡ WALTER SIDGREAVES. The Spectrum of *o Ceti* as Photographed at Stonyhurst College Observatory. *Mon. Not. Roy. Astr. Soc.*, Vol. 58, p. 344, April, 1898.

¶ W. W. CAMPBELL. Note on the Spectrum of *o Ceti. Astrophysical Journal*, Vol. IX, p. 31, January, 1899.

When the seeing is good, an exposure of ten minutes will give a satisfactory negative of a star to which the Draper Catalogue assigns the photographic magnitude 5.0. If *o Ceti* were of about the tenth photographic magnitude at minimum, it would require, roughly, an exposure one hundred times as long as a fifth-magnitude star, or about sixteen hours. Some of the light being in bright lines, we should expect a still longer exposure to be necessary. This estimate agrees with my experience. About July 1, 1902, an hour's exposure, just before daylight, could be made on the star, and it was bright enough to photograph in that time. An exposure of six hours at the time of minimum, using the fastest photographic plate obtainable, was not sufficient to produce a measurable image, although much could be seen in a qualitative way. On January 5, 1903, the date of my last negative, an exposure of five hours, beginning soon after sunset, was possible. Early in March, 1903, the spectrum was again bright enough to record itself with a fairly short exposure; and, in the absence of the writer, Messrs. REESE and CURTIS were ready to make an attempt, but bad weather prevailed.

As is well known, *o Ceti* and the other long-period variables have absorption spectra of SECCHI's third type. Some observers have found the region from $H\gamma$ toward the red crossed by a series of dark bands, with edges sharp toward the violet, and they report that from $H\gamma$ to the ultra-violet the dark-line spectrum is very similar to that of the Sun. At first glance this seems to be verified by my plates, but a closer study shows the details to be very different.

In comparing the star spectrum with the solar spectrum, it was not found best simply to measure the plates and then look for coincidences in ROWLAND's table. It is easy to find a line in the table which agrees in position with the one on the plate, but the intensities may be very different. The method adopted was to compare a plate of *o Ceti* with one of the sky. The two negatives, film sides together, were examined under the microscope with a low power.

The strong calcium lines *g*, *H*, and *K*, are present in the spectrum of the star, the *g* line being much more intense than in the solar spectrum. The strong iron lines of the Sun are not so prominent in *o Ceti*; in fact, they do not show with low

dispersion. Of the large number of lines in the star spectrum, there are few which coincide with lines of like intensity in the solar spectrum.

The absorption spectrum of *Mira* was measured accurately on six plates. Each plate was measured and reduced independently, so that a faint line might be measured on one plate without being noticed on any of the others. This does not mean that it had developed, or that its intensity had changed. Such lines, of which many were measured, could be easily obscured by an irregular arrangement of the silver grains. The best method of verifying changes is to examine different plates simultaneously, in pairs, under the microscope. This has been done, and all changes in intensity or character have been noted.

About one hundred lines were measured in the region from λ 3900 to λ 4400. Residuals have been formed by subtracting the mean wave-length of each line from its measured wave-length on each plate.

The residuals for each plate have been averaged; and if there were any change in the velocity it would appear in the mean residuals. The arithmetical means of the residuals to the violet of λ 4400, and the corresponding velocities in kilometers per second, are as follows:—

Date.	Plate No.	tm.	km.
1902, July 6	7 C	+0.02	+1
16	13 E	+0.06	+4
Aug. 4	25 F	—0.03	—2
11	27 D	—0.02	—1
25	28 D	—0.03	—2
1901, Aug. 17	2235 D	+0.02	+1

When it is remembered that all lines, good and poor, were included in the means, and that these plates were taken with a one-prism instrument giving a dispersion of but one fifth of that of the regular Mills spectrograph, the range of only 6^{km} on six plates is very satisfactory. None of the plates taken later in 1902 are good enough to afford comparable conclusions as to the velocity; and it was thought best to measure only first-class plates in this connection.

The result that the star's velocity was constant over a certain period was derived without assuming the coincidence of

any of the star lines with lines of the solar spectrum, or with other known lines. A determination of the actual radial velocity requires an assumption as to what the wave-lengths of the star lines would be if they were not affected by velocity. Agreements of star and solar lines were looked for, by direct comparison of the star plates with a solar plate, and only ten coincidences were found. Six of these lines were good enough to be used for determination of velocity, and they give $+66^{km}$.

CAMPBELL in 1898 found $+62^{km}$ with the three-prism instrument. The interval between August 29, 1898, the date of his first plate that year, to August 25, 1902, the date of my last plate which was measured, is equal to 130 days more than four periods of 331 days. The radial velocity has therefore been observed to be constant over about two fifths of the period of light change.

To determine more coincidences, I have measured one of the high-dispersion plates of *o Ceti,* taken by Dr. CAMPBELL in 1897. Although the plate is under-exposed, about seventy lines were measured between λ 4300 and λ 4420, and more than twenty coincidences were found by direct comparison with a solar plate. My measures of this plate give a velocity of $+63^{km}$.

A brief summary of the number of dark lines of different elements observed in the spectrum with both three- and one-prism instruments, may be of interest:—

Element.	No. of Lines.
Ca	6
Fe	11
Cr	9
V	11
Al	2
Sr	1
Mn	3 } ?
Ti	2 }

There can be no doubt of the presence of the first four elements in the list, and the aluminum and strontium lines are prominent; but manganese and titanium must be considered as doubtful.

On account of the varying instrumental conditions it is

easy to fall into error in judging as to changes in the intensity and character of dark lines. If all the negatives were of the same density and of uniform excellence, it would be easy to note such changes. There is one dark line which showed changes of which the reality is certain. This is the *g* calcium line at λ 4227.84. Measures of its width are necessarily rough, and must depend much upon the judgment of the observer. The measures of two plates are as follows:—

Date.	Plate.	Width.
1902, June 27	2 B	2^{tm}
September 6	33 D	9

Other plates taken between these dates gave intermediate values.

The general impression formed from examining the series of plates is, that many other lines also grew broader as the brightness declined, but this is not certain. The effects of greater width of the slit, reduced intensity of the resulting negative, and flexure and temperature changes resulting from longer exposure, would all tend to make the lines wider and less sharply defined. The *H* and *K* lines are not shown on most of the plates, and nothing can be said as to changes in their character.

A few lines not visible on the early plates became prominent later. Lines of the solar spectrum which certainly coincide with these have not been found.

The prominent bands in the spectrum of *Mira* have been considered by some observers as a series of dark bands, with sharp edges toward the violet, and shading off toward the red. Others think them to be bright flutings like those of the arc spectrum of carbon. For convenience, they will be considered, in this paper, as dark absorption bands. On the plates of **o** *Ceti* and other third-type stars taken with Spectrograph I, the bright portions of the banded spectrum are certainly brighter relative to the region above $H\gamma$, where there are no bands, than are the corresponding portions of the spectrum of a solar-type star. However, the dark portions are fainter than the same places in the solar type of spectrum.

No attempt was made to determine the position of the more diffuse ends of the bands. In many cases the intensity changes

gradually from head to head, there being heavy absorption at the sharp edge, the spectrum growing uniformly brighter to the next line of demarcation.

SIDGREAVES, on comparing the spectrum of *o Ceti* with that of *α Herculis* and other third-type stars, found a difference in the wave-length of the same band in different stars. For the head at λ 5447 in *o Ceti,* he found the position of λ 5458 in *α Herculis,* and intermediate values for *α Orionis* and *β Pegasi.* He suspected these discrepancies to be due to instrumental causes, but of this he was not certain. His work being done with an objective prism, he had no comparison spectrum with which to test the reality of the observed differences.

Along with the work on *o Ceti* in 1902, plates were taken of *α Herculis, β Pegasi, ρ Persei, α Ceti,* and *α Orionis.* As these stars are all bright, the exposures on them were comparatively short, from five minutes to one hour. Isochromatic plates were used, so that a range of spectrum as far to the red as λ 5600 was covered. They were measured only for the positions of the heads of the bands. In the spectrum of *Mira* there are few dark lines shown in the region of the bands, but in the others many lines were recorded. Where there are more lines the bands are less prominent, and in the case of *α Ceti* and *α Orionis,* only three bands could be measured, while twenty-one were measured in the spectrum of *o Ceti.*

The measures of the bands give accordant results for the different stars, and in but few cases is there a discrepancy of more than one tenthmeter. My measures of the band near λ 5447 give λ 5446.8 from five stars, no star giving a value differing as much as one tenthmeter from the mean. *o Ceti* gives exactly the same wave-length as the mean of the others.

As far as I know, the identification of the bands of the third-type stars has not been accomplished. If the division at λ 5165.9 be considered as the head of a bright band, it is in close agreement with the head of the third carbon band at λ 5165.3, as measured by KAYSER and RUNGE. The head at λ 4737.1, measured in *α Herculis,* may also correspond to their fourth carbon band, λ 4737.2. These two coincidences are the only ones I have found, and we certainly need more evidence before drawing any conclusions from them.

SIDGREAVES found that the continuous part of some regions

of the star's spectrum changed in relative intensity as the star grew fainter. These changes have been verified in the present work.

SIDGREAVES'S plates showed that as the star declined in brightness, the intensity of the bright portions of the spectrum between λ 4300 and λ 5000 grew less relatively to that of the region near λ 5500. My plates show a decrease in intensity of the region from λ 4300 to λ 5000 relative to the continuous spectrum from λ 4000 to λ 4300.

These changes in intensity have been described as changes in the continuous spectrum, but they may be simply the fading out of some bright bands.

The most noticeable and interesting features in the spectrum of *o Ceti* are the bright lines. The great brilliancy of some of the hydrogen lines, when the star was near its maximum, has been recorded by several observers. The peculiar fact was noticed, that H_α, $H\beta$, and H_ϵ were apparently missing, while others of the hydrogen series were very bright. Photographs, which showed H_γ and $H\delta$ as intense, gave no trace of $H\beta$ and H_ϵ. SIDGREAVES, in 1898 and 1899, found something which from its position might be the bright $H\beta$, but he did not consider it as certain. It has been seen bright on some plates at Harvard. [Vol. 28, Part I, H. C. O.] Mr. WRIGHT found H_ϵ distinctly bright on a plate which he had taken in August, 1901. $H\beta$ and H_ϵ were recorded as bright lines on all the dense negatives taken with Spectrograph I. They seem to have grown stronger relatively to the other hydrogen lines and also to the continuous spectrum as the star grew faint.

An attempt was made to observe H_α visually, but without success, on the night of September 6, 1902, when the instrument was changed to adapt it for visual work. Corresponding to the bright well-defined H_α of the comparison spectrum there was continuous spectrum, but no bright line in the star. Mr. WRIGHT was present and verified the observation. H_α should be looked for when *Mira* is again at a maximum.

The wave-lengths of the bright lines show no more change than do those of the dark lines. The average residual for each plate has been computed and there is no sign of variable position. A comparison of these average residuals with those of the dark lines is as follows:—

Date.	Plate No.	Dark Lines.	Bright Lines.
1902, July 6	7 C	+0.02	+0.01
16	13 E	+0.06	+0.04
Aug. 4	25 F	—0.03	—0.03
11	27 D	—0.02	—0.03
25	28 D	—0.03	+0.03
1901, Aug. 17	2235 D	+0.02	—0.04

These average residuals are all so small that the agreement in sign for some cases is of little significance.

The wave-lengths of the bright lines and the identification of some of them is given in the following table.

There can be no doubt that the hydrogen series is present. Metallic lines which seem to coincide in five cases are given, but in spite of the accuracy of the measures, we must consider the question of their identity to be still open.

IDENTIFICATION OF BRIGHT LINES.

o Ceti λ.	Tabular λ.	Displacement. tm.	Substance.	Authority for λ.
3751.2–	3750.15	+1.0–	H_κ	AMES.
3771.52	3770.7–	+0.82	H_ι	AMES.
3798 76	3798.0–	+0.76	H_θ	AMES.
3836.20	3835.6–	+0.60	H_η	AMES.
3853.51				
3889.91	3889.15	+0.76	H_ζ	AMES.
3906.36	3905.66	+0.70	Si 12	ROWLAND.
3908.18				
3933.45				
3939.10				
3968.49				
3970.87	3970.18	+0.69	H_ϵ	ROWLAND.
4007.74				
4102.66	4101.89	+0.77	H_δ	WRIGHT.
4202.91	4202.20	+0.71	Fe 8	ROWLAND.
4216.71				
4234.12				
4308.70	4308.08	+0.62	Fe 6	ROWLAND.
4341.33	4340.63	+0.70	H_γ	ROWLAND.
4373.61				
4376.78	4376.11	+0.67	Fe 6	ROWLAND.
4571.82	4571.26	+0.56	Mg 5	ROWLAND.
4862.34	4861.53	+0.81	H_β	ROWLAND.

It should be noticed that a bright line developed on each side of each of the strong dark calcium lines, *g, H,* and *K.* Without looking at the plates, this might seem to be due to a double reversal of the calcium lines. Their appearance is not such, however. Mr. WRIGHT also examined the plates with this in mind, and in his judgment the lines are separate bright lines and the phenomenon is not one of double reversal.

Several attempts were made, in June and July, 1902, to secure photographs of the spectrum of *Mira,* with the regular three-prism instrument. It was impossible, however, to make an exposure long enough to record the continuous spectrum. The only features recorded were H_γ and two other bright lines. H_γ was single on all the plates. It seemed nearly monochromatic, but was a little sharper on the violet than on the red side. It had the same appearance as that found by CAMPBELL in 1898, at about the same interval after the star's maximum. In 1898 he found that H_γ was triple from five to two weeks before maximum. Before observations of *o Ceti* were begun in 1902, it had been intended to make polariscopic tests for Zeeman effects in the bright lines; but they were found single on the first photographs, and no observations for polarization were attempted. These should certainly be made when it is again possible to observe the star at maximum. Measures of the three-prism plates give the following displacements of H_γ in tenthmeters.

Date.	Plate No.	tm.
1902, July 2	2446 F	+0.65
2	2447 A	+0.68
21	2470 D	+0.65
Aug. 18	2505 E	+0.61
	Mean	+0.65

It is interesting to compare the measures of plates taken in 1902 with those of 1898. CAMPBELL also observed the bright lines near λ 4308 and λ 4376. They were also measured on the high-dispersion plate of August 18, 1902. In the following scheme, under the heading "Bright Lines," is given the actual observed displacement of each bright line, corrected for the Earth's motion. Under "Dark Lines" is given an assumed

displacement which corresponds to that of the absorption-lines in the spectrum.

Line.		CAMPBELL, 1898. Three Prisms. Bright Lines: tm.	CAMPBELL, 1898. Three Prisms. Dark Lines, +62km. tm.	STEBBINS, 1902. Three Prisms. Bright Lines. tm.	STEBBINS, 1902. One Prism. Bright Lines. tm.	STEBBINS, 1902. One Prism. Dark. Lines, +66km. tm.
$H\delta$	4101.89	+0.64	+0.85	......	+0.77	+0.90
Fe?	4308.08	+0.60	+0.89	+0.61	+0.62	+0.95
$H\gamma$	4340.63	+0.64	+0.90	+0.65	+0.70	+0.96
Fe?	4376.11	+0.61	+0.91	+0.66	+0.67	+0.96

The dark lines in this region of the spectrum are apparently displaced about 0.25 tenthmeter farther to the red than are the bright lines. The results obtained with one prism are systematically larger than those obtained with three prisms. This may be partly due, in the case of $H\gamma$ and $H\delta$, to over-exposure on many of the plates. Since the lines seem to shade off toward the red, greater exposure probably slightly increases the apparent wave-lengths. However, since the displacements of the other hydrogen lines, which were not over-exposed, are about the same as those of $H\gamma$ and $H\delta$, this effect is probably not large. The difference between the results of 1898 and 1902 is due, no doubt, to personal errors.

The bright lines at $\lambda\lambda$ 4308 and 4376, marked as possibly due to iron, are of peculiar interest. The appearance of each, on some of the plates, is of a bright line with an adjacent dark one on the red side. If the bright lines be due to iron, they are displaced by the same amount as the bright hydrogen lines; and if iron produces the absorption components, the displacements are equal to those of other dark lines.

A glance at the series of plates showed that there were many changes of intensity among the bright lines, both relative to each other and to the continuous spectrum. The lines at $\lambda\lambda$ 4202, 4308, and 4571 all became brighter than the hydrogen lines. Of these three, only λ 4202 was visible on the early plates. λ 4571 did not exist at first, but appeared when the star was of about magnitude 5.4, and as *Mira* grew faint this line became the most prominent object in the spectrum.

$H\gamma$ and $H\delta$ could not be seen on plates taken near minimum, although they were easily observed a month before. On account of underexposure it can not be said whether the other bright hydrogen lines disappear or not.

Until this star has been successfully followed through all its phases, it is obviously too soon to advance any theory to account for the observed changes in its spectrum or in its brightness. The light-gathering power of the great refractor is not sufficient to follow the spectrum satisfactorily, at least not on the dispersive scale used by me. An ideal equipment for work on variables would consist of a large reflector which could be used for this purpose alone, with spectrographs of various dispersive powers arranged for use in all parts of the spectrum.

The apparent constancy of radial velocity is strong evidence that the variations in brightness are not due to the influence of a companion star, unless, indeed, the companion were of very small relative mass, were moving in a very eccentric orbit, and approached very close to the primary. The displaced system of bright lines could not belong to such a companion, as their wave-lengths are apparently constant. The large irregularities in the period of the light-curve practically preclude the question of a binary system, though perhaps not absolutely so.

The remarkable distribution of light in the hydrogen series seems as yet impossible to explain. Miss CLERKE has explained the apparent absence of H_ϵ by assuming the hydrogen to be at a lower level in the star's envelope than the calcium layer, the H calcium absorption destroying the H_ϵ radiations. This theory may still be true, though the existence of a faint bright H_ϵ has been proven. However, $H\beta$ and H_α are much more reduced in intensity than is H_ϵ; and with them there is no evidence of overlying absorption strata. It is usually expected that the bright hydrogen series will diminish in intensity from red toward the violet. This appears to hold even for new stars, in which the disturbance has been very sudden, though exception should perhaps be made for H_α when new star spectra approach the nebular form. The supposition that in *Mira* the hydrogen series may regularly decrease in brightness from violet to red is not tenable, as the diminution from H_γ to H_β is entirely too great. Inasmuch as the bright lines are strongly shifted (to the violet with reference to the dark-line system) from their normal positions apparently by causes other than radial velocity and pressure, it seems probable that the peculiarities of the hydrogen-line intensities are due also to causes

now unknown to us. The presence of the bright iron lines λ 4202, λ 4308, and λ 4376, the absence of others of the same element, and the diversity of structure observed by CAMPBELL in the triple $H\gamma$ and $H\delta$ bands are perhaps due to similar unknown causes.

The great variations of relative intensity observed in the hydrogen and other bright lines, and in the continuous spectrum, show that the star's decrease in light is produced by other causes than general absorption.

Considering all the evidence, it seems reasonably certain that the star's variation in brightness is due to the action of internal forces.

I beg to acknowledge my indebtedness to Director CAMPBELL, who provided the necessary apparatus and made valuable suggestions during the course of the work; to Messrs. WRIGHT and REESE, for continual advice and assistance; and to Dr. H. D. CURTIS, for enlarging the negatives for reproduction.

May 1, 1903.

NOTES ON VARIABLE STARS.

By ROSE O'HALLORAN.

Y Cassiopeæ.

The variation of this star, which was discovered on the photographic plates of Harvard College Observatory a few years ago, ranges from 9.8 to 13th magnitude.

According to the comparison-stars of 10.2 and 12th magnitude close above, it was of 11.3 magnitude on the 1st and 2d of August, in 1902, and on October 26th and 31st, and November 3d it had increased to 11th magnitude.

W Aurigæ.

Having become invisible in last December, the predicted maximum was looked for towards the middle of January of this year.

On the 14th, 17th, and 27th, and on February 1st it was still invisible, though a comparison-star of 12th magnitude was seen. The period of *W. Aurigæ* seems to be irregular.